Technical Note

Effect of grain characteristics and cement content on the unconfined compressive strength of artificial sandstones

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1. Introduction

Hydrocarbon resources are often found in sandstone formations, but the lack of access to original cores from very deep drilling and the need for testing large numbers of samples, for example studies on formation damage like sand production, have led to the use of analogous artificial specimens for experimental tests. To that purpose, artificial samples should be made as similar as possible to the original core samples. Unconfined compressive strength is amongst the main characteristics of formation rock, which should be considered when making artificial samples. This technical note presents results of an experimental investigation on the effect of different parameters on the UCS of artificial sandstone samples. These tests were originally performed to optimize the properties of artificial specimens used in physical modeling of sand production [1,2].

The factors that affect the strength of sandstones have been researched extensively, and from the available literature they could be summarized as follows:

\textit{Cement content}, which has a direct relation with the strength: increasing cement content has the effect of increasing the strength of sandstones (e.g. Fell sandstone) [3]. Consoli et al. [4,5] studied the effect of different parameters such as porosity, curing time and cement content on the unconfined compressive strength (UCS) of cemented sand. For specimens with the same curing time and grain size distribution they found a unique power-law relation between the UCS and the ratio of porosity to volumetric cement content (also called the porosity-cement index). Only two types of sand were used in their study, a uniform fine sand and a well-graded decomposed granite, and therefore it is difficult to draw clear conclusions on the effect of the grain mean size or grain size distribution on the UCS of the cemented soil.

\textit{Grain packing}, which has a direct relation with the strength: the strength of sandstones can also be influenced by the packing of particles, which is usually assessed in terms of packing proximity and packing density [6]. The packing density, grain-to-grain contact and grain area ratio determine the closeness or spread of grains, also called compactness [7,8]. High packing density can lead to high strength, as was found in two sandstones from the United Kingdom which are Fell sandstone [3] and Sherwood sandstone [9]. On the other hand, low packing density typically characterizes weak sandstones [10]. Better grain packing also usually results in lower porosity, and it could be advanced that there is a direct relation between porosity and grain packing.

\textit{Grain contact}: the nature of grain packing and the type of grain contacts also play a role in the strength of weak rocks, so that densely packed specimens with interlocked grains and concavo-convex and sutured contacts typically show high strengths in excess of 40 MPa, while specimens with floating or tangent contacts and few sutured contacts show much lower strengths, such as the sandstones from the Clarens Formation (South Africa) [11]. Similar results were found on a variety of sandstones, for example weak sandstones from the Sherwood Sandstone Group were found to be poorly compacted with grain contacts predominantly tangential [12], while high packing density and percentage of sutured contacts present in Kozlu sandstone (Turkey) lead to a high value of strength [13]. This corroborates Dobereiner and De Freitas’ [10] and Dyke and Dobereiner’s [14] suggestion that the amount of grain contact (i.e. the ratio of the contact length of a grain with its neighbors to its own total length,
measured in two dimensions) has a major influence on the strength and stiffness of sandstones. Therefore a higher amount of grain contacts results in stronger samples. Grain contacts may also depend on grain size distribution, and well-graded sandstones may have a higher amount of grain contacts.

**Grain size:** most sedimentary (granular) rocks such as sandstone are composed of grains, pores and bonding cement. Deformation of these rocks involves changes in shape and size of one or more of these constitutive elements [15]. The grains form the skeleton of the material, the strength of which depends on the strength of the grains themselves and their interaction with each other as well as interaction with cement and matrix. Using greywacke as a research material, Fahy and Guccione [16] showed that a decrease in grain size was associated with a higher strength in greywacke, while Singh [17] found that an increase in grain size results in a decrease in its uniaxial compressive strength. Similar results were found for sandstones from the Sherwood Sandstone Group (Nottinghamshire, UK) [9]. However, for some sandstones the particle size does not seem to influence their strength. Fell sandstone (Northumberland, UK) [3] and sandstones from the Sneinton formation (Nottinghamshire, UK) [18] or Donetski rock (Ukraine) [19] are some examples. Thus there is evidence that for some cases finer grains would result in stronger sandstones [16] but for some cases it has an inverse relation [17,9]. There are also works, which reported no clear relation between grain size and strength [3,18,19].

While the effects of cement content, grain packing and grain contact on the unconfined compression strength are rather well understood, the influence of the grain size distribution (i.e. size and uniformity) has been less studied so there are no clear results. The reported relation between UCS and the ratio of porosity over cement content proposed by Consoli et al. [4,5], which was shown to be reasonable for some cemented soils, was also not investigated for sandstones.

This technical note re-establishes and extends the correlation between UCS-value and specimen characteristics using data from a large number of unconfined compression strength tests on artificially cemented sand specimens with different host sand sources, varying particle size distributions, mean grain size (D50 between 0.09 and 1.28 mm) and varying cement content (12% to 30%). It is shown how the particle size, particle shape and the uniformity of the particle size distribution play a role on the strength of the artificial sandstones in addition to porosity and cement content.

### 2. Testing material and procedures

A series of unconfined compression strength tests (118 in total) was performed on a group of artificial cylindrical sandstone samples of NX size and a height to diameter ratio of around 2.5. The NX size, with a diameter of 54 mm, is a common diameter size for UCS tests, and a ratio of 2.5 between height and diameter is commonly chosen to avoid effects of sample size and optimize uniformity of stress and strain in the sample. This is also in line with the ASTM [20] standard for sample preparation for such tests, which specifies that the specimens must have a length-to-diameter ratio (L/D) of 2.0 to 2.5 and the diameter of the sample must not be less than 47 mm.

In order to prepare specimens with different UCS and porosity, different cement contents and compression levels during preparation were used. These specimens can be categorized in three groups by sample properties. The first group consisted of fifty-two artificial sandstone specimens having seven different mean grain sizes. The second group consisted of forty-two sandstone specimens having the same mean grain size (D50 of 0.4 mm) and four different coefficients of uniformity (C_u). The third group consisted of twenty-four specimens with the same grain size distribution and different cement contents; half of these specimens were made with rounded grains and the other half with angular ones. The number of tested samples for each group and different scenarios is given in Table 1.

#### 2.1. Preparation of artificial sandstone samples

The grains used in the first group were obtained by crushing and sorting quartz crystals from a mine in Garmsar, Iran. The grains are mostly angular and their composition is dominated by quartz. SiO2 makes up about 97.6% of the grains and the other remarkable composition is Al2O3, which makes up about 0.48% of the material. The specimens were prepared based on seven different grain size distributions (Fig. 1a), three of which (distributions A, B and E) correspond to the particle size distribution of the sandstone recovered from Asmari formation in an Iranian oil field. Table 1 also gives the main characteristics of the specimen particle distribution in all groups, including the mean particle size, D50, and the curvature calculated using the coefficient of uniformity, C_u.

Fig. 2 shows microscope pictures of the coarsest and finest grains of this group (distributions A and G). Because the original purpose

### Table 1
Grain size distribution and average grain shape factors of the samples. C_u is the coefficient of uniformity.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of the tested samples</th>
<th>Grain characteristics</th>
<th>Particle shape factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Particle size distribution</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D_{10} (mm)</td>
<td>D_{50} (mm)</td>
</tr>
<tr>
<td>First group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>17</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>B</td>
<td>17</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>0.12</td>
<td>0.21</td>
</tr>
<tr>
<td>D</td>
<td>3</td>
<td>0.17</td>
<td>0.26</td>
</tr>
<tr>
<td>E</td>
<td>2</td>
<td>0.18</td>
<td>0.38</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>0.43</td>
<td>0.79</td>
</tr>
<tr>
<td>G</td>
<td>7</td>
<td>0.74</td>
<td>1.28</td>
</tr>
<tr>
<td>Second group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>6</td>
<td>0.32</td>
<td>0.40</td>
</tr>
<tr>
<td>S2</td>
<td>12</td>
<td>0.23</td>
<td>0.40</td>
</tr>
<tr>
<td>S3</td>
<td>12</td>
<td>0.17</td>
<td>0.40</td>
</tr>
<tr>
<td>S4</td>
<td>12</td>
<td>0.13</td>
<td>0.40</td>
</tr>
<tr>
<td>Third group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rounded</td>
<td>12</td>
<td>0.22</td>
<td>0.61</td>
</tr>
<tr>
<td>Angular</td>
<td>12</td>
<td>0.22</td>
<td>0.61</td>
</tr>
</tbody>
</table>
of the tests was to optimize the properties of artificial specimens used in physical modeling of sand production, the number of tested samples for each grain size distribution was chosen to be different. The Second and Third groups of specimens were made with riverbed sands (Fig. 3). Those sand particles were round as usually expected for that type of grain, and used uncrushed in specimens of the Second group. In the Third group, half of the specimens were made using some of the round grains that had been subjected to crushing and thus became angular, and the other half consisted of the intact round grains.

The river sand grain particles used in the Second and Third groups include different minerals. The main minerals were mostly quartz, feldspars, carbonates, different types of mica and polycrystalline rock fragments. These grains include less amount of quartz in comparison to the grains of the First group.

The average shape factors of the grains are shown in Table 1. These values were obtained from dynamic particle image analysis using a Qicpic laser scanner apparatus that enables capturing particle images between 1 μm and 20 mm [21]. Parameters quantifying the size and shape of the particles can be determined, such as the aspect ratio (ratio between the Feret-minimum and Feret-maximum diameter), the sphericity (ratio of the equivalent circle perimeter to the real perimeter), and the convexity (calculated from the ratio of the projected particle area to the gross area including any re-entrant sections). It is observed that almost all grain shape factors are similar for different specimens within a group, except convexity for specimen A, which is lower than other samples. As expected, shape factors are higher for specimens with rounded grains in the Third group in comparison to specimens with angular grains. All shape factors in the Second group are similar to the factors related to the specimens with rounded grains in the Third group. Fig. 4 shows some examples of the grain shapes provided by Qicpic for different sizes of grains used for making specimens in the Second and Third groups.

The specimens were prepared by mixing the sand of the selected grain size distribution with cement and water. Portland cement type II, which is common in construction industry, was used. Water was mixed with the cement and grains to reach a homogeneous paste. The water content was 15% for the fine-grained specimens ($D_{50} < 0.3$ mm), and 7.5% for the coarse-grained specimens ($D_{50} > 0.3$ mm). The tests showed that the maximum amount of water content that can be tolerated in a coarse-grained sample before it becomes a slurry is 7.5%. Higher water contents caused segregation of the cement and the water to drain, resulting in a non-homogenous specimen. The cement-sand mixture was poured into a 54 mm diameter mould in about ten different layers and each layer was compressed for a fixed time (10 s) under a fixed pressure for all the layers. Different pressure levels (1, 3, 5 and 7 MPa) may be applied during preparation for different specimens. The pressure was applied using a platen, piston, jack and hydraulic pump. The applied pressure was controlled carefully during the compaction so samples of same composition but with different porosities could be achieved by applying different pressures during the sample preparation. The coarse-grained specimens were cured in water for twenty-one days and the fine-grained specimens for fourteen days. Tests showed that the specimens reached their maximum strength within the duration of their treatment so the strength was considered to have reached a stable state before testing.

The porosity of the samples was determined by imbibition method after completion of the treatment. The samples were cut at the required length and the end surfaces were ground before placing in the apparatus to meet the requirements of the ASTM standard [20].
Fig. 2. Sand grains used to make the First group of samples; (a) is related to sample A and (b) is for sample G.

<table>
<thead>
<tr>
<th>Angular grains (Third group)</th>
<th>Round grains (Second and Third group)</th>
<th>Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Angular grains" /></td>
<td><img src="image2" alt="Round grains" /></td>
<td>1.19-1.68</td>
</tr>
<tr>
<td><img src="image3" alt="Angular grains" /></td>
<td><img src="image4" alt="Round grains" /></td>
<td>0.84-1.19</td>
</tr>
<tr>
<td><img src="image5" alt="Angular grains" /></td>
<td><img src="image6" alt="Round grains" /></td>
<td>0.50-0.84</td>
</tr>
</tbody>
</table>

Fig. 3. Microscope image of angular and round sand grains of different sizes used to make the samples in the Second and Third groups.
2.2. Testing apparatus and procedure

All specimens were subjected to uniaxial compression using a rigid MTS 815 apparatus with a constant displacement rate of 0.007 mm/s. This rate was chosen based on previous experience, which showed that high rates affect the UCS value. Chosen rate was slow enough to minimize the possible effects of displacement rate on UCS. The characteristics of the platens ensured that the required standard of the ASTM for UCS test in rocks [22] was met as the top platen spherically seated and the other plane was a rigid platen.

The failure modes observed for most of the samples were double shear and shearing along a single plane, except for the specimens with UCS higher than 20 MPa, which failed with axial splitting. These failure modes have been addressed for sandstones, for example Basu et al. [23]. The grain size distribution seems to have had no effect on the failure mode of the tested samples.

Fig. 4. Examples of particle shapes obtained from the Qicpic dynamic image analyzer for angular and round sand grains with different sizes used to produce the samples in the Second and Third groups.
3. Effect of cement content and porosity on the UCS

In this study the cement content was calculated as the ratio of the mass of used cement to the total dry mass of the specimen. The cement content is a predominant factor affecting the strength of artificial sandstone samples. Fig. 5a shows the relation between cement content (CC) and UCS for specimens of the First group. Only the data for specimens with a mean grain size $D_{50}=0.09$ mm are shown for illustration. Data points in the graph are categorized based on the static compression applied to the layers during the preparation. The different specimens were subjected to different compression stress levels during sample preparation. The data seem scattered and no significant trend can be defined. However it appears that for a given grain size distribution, there are clear relations emerging for specimens prepared using the same level of compression during preparation. Straight lines can be drawn for different preparation compression stresses through the data. Linear relationships have also been found by other researchers on other types of host sand, for example weathered sandstone [4] or crushed granite [24].

Porosity, which has a close relation with the arrangement and size distribution of grains, also affects the UCS. Fig. 5b shows the relation between porosity ($\phi$) and UCS for the specimens. There is less scatter than the data related to the effect of cement on UCS. Similarly to before, it can be seen that data seems to be more consistent for different compression pressures used for preparation.

For a single particle size distribution and given preparation method, it can be concluded that there is a direct relation between cement content and UCS and an inverse relation between porosity and UCS, similarly to what was presented in [18,19]. According to [18], there is a unique relation between the ratio of porosity to cement content and the unconfined compressive strength for cemented sands. With the view to use parameters that have a positive effect on the strength, UCS was plotted against the ratio of cement content to porosity (CC/$\phi$) i.e. the inverse to the ratio proposed by [18] (Fig. 5c). Without readjusting the ratio (CC/$\phi$) as was suggested by [18] by using an exponent and a power law relation, a straight line can be drawn through the data points. The same can be seen for all the data, as shown in Fig. 6 where the data
for all tests for different values of $D_{50}$ are plotted. It is usually expected that the UCS of samples with very low cement ratio tends to zero at zero cement content. In Fig. 6 the extensions of the straight trend lines do not pass through the origin, thus it was assumed that it was curved at low cement content.

4. Effect of particle size distribution on UCS

Fig. 6 shows the relation between UCS and ratio of cement content to porosity for all grain sizes in first group. The scatter in the data hints that there are other factors influencing the unconfined compressive strength of the cemented sand. The effect of the mean grain size of the assemblies or the curvature of the grain size distribution may be responsible for the scatter. Two different linear trends can be distinguished in Fig. 6, one for specimens with mean grain sizes of 0.09 mm and one for the specimens with other mean grain sizes, which vary between 0.18 mm and 1.28 mm. Proposed trendlines and related equations are shown in Fig. 6. It seems that the ratio of cement to porosity results in stronger specimens for those made by grains with mean grain size of 0.09 mm (type-A), which apart from the different size were prepared and tested in the same way as all other samples. It is noticed that the shape factors of grains used to make type-A specimens are lower than factors for all others in the First group. This may explain the higher strength. This is explored later in this technical note.

The coefficient of uniformity $C_{u}$, reported in Table 1, is very close for different types in the First group (between 1.67 and 2) except for type-E that has a higher $C_{u}$ of 2.56. Since results of type-E specimens are quite similar to the results of other types (except type-A), it seems that the different trends noticed earlier may therefore not be explained based on differences of $C_{u}$. In addition, the type-A samples, which have a different trend, have an almost similar $C_{u}$ to other types (except type-E). The effect of the particle size distribution remained unclear. Therefore additional tests were designed in order to investigate the effect of the grading on UCS.

Forty-two of the tested specimens were prepared with round riverbed sand grains of given mean grain size but with different uniformity coefficients varying between 1.32 and 5.12 (types $S_{1}$ to $S_{4}$ in Table 1). The value of $C_{u}$ represents the curvature of the grain size distribution curve. All the specimens have the same $D_{50}$ of 0.61 mm. They were prepared with varied cement content and compression level. The effect of $C_{u}$ can be highlighted from the tests performed at similar mean grain size and grain sources. The UCS values are plotted against cement content in Fig. 7a. The data are scattered but they indicate that for specimens with the same cement content, the increase in strength observed as the $C_{u}$ value increases is only due to the associated increase in packing density. Dal Rosa et al. [25] had found that similarly, the increase in strength observed on cemented sand specimens cured under stress can be explained by the decrease in void ratio caused by the curing stress.

5. Effect of angularity of grains on UCS

The two trends distinguished for the relation between UCS and cement content to porosity for samples in the First group (Fig. 6) could not be explained based on the difference in mean grain size and $C_{u}$. Table 1 shows the grain shape factor of the different tested sands. Type-A sand has the lowest aspect ratio and convexity in the First group. The sphericity is rather similar for all types and type-A’s sphericity is almost at average. It seems that sand grains related to this type are the most angular one. This high angularity can be considered as the reason for the higher UCS level of specimens made using this type, but to confirm this a Third group of specimens was tested. Grains were collected from rounded.
higher strength and compressibility [26]. The mechanisms by example higher angularity leads to higher minimum density, shown to have an effect on the uncemented soil behavior, for a more dominant effect. The shape of sand particles has been particle distribution curve and grain size, angularity seems to have cement content to porosity. In comparison with the curvature of UCS and the ratio of cement content to porosity. The effect of the average grain size and the coefficient of uniformity is not clear from the relation between UCS and the ratio of cement content to porosity, even though samples with better-graded particle size tend to have higher strength for same values of cement content. The effect of the grain shape is clearer. Specimens made by angular grains have higher UCS for same cement content, porosity and cement content to porosity ratio in comparison to those, which were made by rounded grains.

References